Measuring the Age of the Lathrop Wells Volcanic Center at Yucca Mountain

B. Turrin *et al.* (*1*) argue that conventional K-Ar and $^{40}Ar/^{39}Ar$ age determinations and paleomagnetic data provide a definitive age assignment of approximately 136 ka (thousand years ago) to 141 ka for the Lathrop Wells volcanic center with an error of less than 10,000 years. This conclusion is tendered despite replicate age determinations that extend over almost three orders of magnitude. Turrin (*1*) and other also conclude (*2, 3*) that the Lathrop Wells volcanic center is a simple monogenetic center, and so revert to an earlier interpretation (*4, 5*) that was made before studies revealed the complexity of the volcanic stratigraphy (*6–9*).

The geologic map and stratigraphic nomenclature of the Lathrop Wells volcanic center presented by Turrin *et al.* (*1*) were extracted and modified without apparent reference to the original publication of these field studies (*10*). Stratigraphic units separated by soil-bounded unconformities were modified or not accounted for in their interpretation (*6, 8*). These unconformities indicate a hiatus in eruptive activity of significantly sustained time (at least 10^3 years) and allow the development of soil profiles that are similar to radiocarbon dated soil sequences within arid regions of the southwestern United States (*11–14*). Without complete stratigraphic sampling, statements regarding the complexity of Lathrop Wells eruptive history offer only an oversimplified stratigraphy. Turrin *et al.* state that their combined flow and scoria unit Ql_3/Qsu [(*1*), figure 1] is younger than the flows and scoria of Ql_5/Qs_5, but they report without any implications a weighted mean of 141 ± 9 ka for the younger rocks and an age of 136 ± 8 ka for the older rocks. In comparison, recently reported thermoluminescence age determination (*8*) of a buried soil between tephra deposits of their unit Qs_5 is 9.9 ± 0.7 ka. Cosmogenic ^3He age determinations (*8*) of surface-exposed volcanic bombs of unit Qs_5 yield ages of 23 ± 4 ka to 44 ± 13 ka. Flows that stratigraphically lie below these tephra and bomb deposits yield a thermoluminescence date of 24.5 ± 2.5 ka for baked soils that underly unit Ql_3 (*8*) and yield a cosmogenic ^3He date of 64 ± 6 ka on exposed bedrock of unit Ql_5 (*8*). The weighted means of the K-Ar and $^{39}Ar/^{40}Ar$ age determinations have insufficient precision to constrain the age of these late Quaternary volcanic flows and tephra separated by soil-bounded unconformites.

Our major criticism of the K-Ar and $^{40}Ar/^{39}Ar$ age determinations of the volcanic center made by Turrin *et al.* is of their method of averaging the age determinations, not of their analytical methods. If the data are compiled as a conventional mean, large 1-σ errors are obtained that overlap and are consistent with the results of every other chronology method used to assess the age of the Lathrop Wells center (*8*). The use of a weighted mean gives age assignments with unrealistically small errors, in that the group age dates range from 20 ka to 947 ka. Yet Turrin *et al.* do not explain why the weighted mean might be more reliable than the conventional mean, nor do they test the validity of the weighted mean method. Our specific concerns are as follows.

1) The age determinations are positively skewed with a mean larger than the median, which indicates influence of the mean by older ages.

2) Turrin *et al.* did not examine the data set with conventional tests for outliers. Evaluation of their data shows that outliers are present where outliers are defined to be more than 1.5 times the interquantile range. The data set is nongaussian, with inclusion of the outliers, and therefore is probably not suitable for description with a weighted mean.

3) Four age determinations were discarded by Turrin *et al.* in the weighted mean data reduction because of "contamination." No systematic criteria were presented for doing so, and recalculation of the data set (*1*) with these four age determinations yields significantly older values of the weighted mean with larger uncertainty.

4) The regression plots in [(*1*), figure 2] show the presence of influential cases which should have been identified to check for errors and suitability to the data set. The influential cases could strongly control the *y*-intercept, the values of which are used by Turrin *et al.* to argue against the presence of excess Ar.

5) There was no discussion of data errors other than analytical in (*1*). Because the $^{40}Ar/^{39}Ar$ analyses were of the matrix of fine-grained basalt (*15*), there is a possible problem of recoil of ^{39}Ar which could give anomalous older ages (*16, 17*).

6) Conventional, whole rock K-Ar data are averaged (*1*) with the $^{40}Ar/^{39}Ar$ to establish final values for the weighted means. However, the whole rock data are not listed in (*1*). Thus it is not clear whether the data set belongs to the same population as the $^{40}Ar/^{39}Ar$ data.

We conclude that the reduction of the data set of Turrin *et al.* with a weighted mean method is unsupported at best and may be invalid if all sources of variance in the data set are not analytical. Their conclusion that the soil and geomorphic studies of the Lathrop Wells center are miscalibrated is not supported by the data.

Turrin *et al.* argue that an angular difference of 4.7° between mean directions of remanent magnetization indicates that the dates of Lathrop Wells eruptive events differ by 100 years. However, angular differences between two paleomagnetic data sets can only be used at best to infer a *minimum* age between stratigraphic units. The geomagnetic field at Lathrop Wells could have occupied the observed directions numerous times during the Quaternary and thus could equally represent eruptions separated by 100, 10,000, 100,000 years, or 1 million years (Ma). For example, Champion (*3*) notes that the flow mean paleomagnetic directions from adjacent 3.7 Ma and 1.1 Ma flows in Crater Flat are "similar . . . but cannot be confused because they have different K-Ar ages and stratigraphic positions." Turrin *et al.* rely on these stratigraphic relations in neighboring Crater Flat, but not at Lathrop Wells (*6–8*).

The conclusion (*1*) that the paleomagnetic data of Qs_5 scoria and Ql_3 flows fall into only two statistically distinguishable groups is unfounded. First, Turrin *et al.* apparently did not sample or analyze several mapped units. Their paleomagnetic record is incomplete (*1–3, 18*), and thus their conclusions are premature. Second, the paleomagnetic data for the 27 sites with flows and spatter and for the 40 core samples from the scoria cone rim are not presented in (*1*) or in their supporting papers (*2, 3, 18*). These data are necessary to assess confidently the statistical validity of their proposed field magnetic groups. Third, on the basis of matching directions of remanent magnetization, Turrin *et al.* infer (*1*) that all scoria and spatter deposits of unit Qs_5 have the same direction as the main scoria cone, but do not note that this conclusion requires the rejection of paleomagnetic data. One-third of 16 reported samples from bombs of the main scoria cone unit (unit Qs_5) were rejected because discordant directions of remanent magnetization revealed apparent "cone slope slumping" (*18*). These rejected data contradict their statement (*1*) that 40 core samples from "bedded" bombs on the rim yield a direction "identical" to that of the flanking spatter cone. Fourth, the conclusion that the Lathrop Wells has a simple eruptive history (*1*) apparently contradicts an earlier interpretation by Turrin *et al.* that the center is polycyclic with "a more complex volcanic history than previously thought" (*18*). This interpretation is based on K-Ar data not presented in (*1*) and paleomagnetic data that indicate a *minimum* of 100 years between eruptions.

A simple eruptive history, together with an older age of the most recent volcanic activity in the region, could justify an assessment of decreased volcanic risk for Yucca Mountain. The polycyclic model, by contrast, requires the consideration of possible additional eruptions within the 10,000-year isolation period required for a potential radioactive waste repository. The latter model could lead to an assessment of increased potential of dispersal of such waste to the environment should a future volcanic eruption compromise the site.

Finally, the simplified volcanic history of Turrin *et al.* (*1*) apparently was not tested by geochemical studies. Recent studies by Perry and Crowe (*9, 19*) at Lathrop Wells center demonstrate that geochemical variations between the main scoria cone and flanking spatter deposits could not result from fractional crystallization of a single magma batch of mixing of separate batches. They conclude (*9, 19*) that the geochemical data are consistent with the interpretation that separate magma batches formed a complex polycyclic volcano characterized by scoria and spatter deposits that were separated in time by a prolonged hiatus in eruptive activity (*6*).

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22 October 1991; revised 6 March 1992; accepted 16 March 1992

Response: The comment by Wells *et al.* centers on three topics: the geologic map and stratigraphy, the K-Ar and $^{40}Ar/^{39}Ar$ data, and the paleomagnetic data.

The unit nomenclature of the geologic map in figure 1 of our report (*1*) is indeed modified from a map by Crowe *et al.* (*2*), of which two of us are co-authors, and we regret not having made that clear. The photomosaic map (*2*), however, is not on a controlled topographic base and has no latitude-longitude marks or north arrow. Most of the contacts on it are shown as either concealed or inferred. We therefore remapped, modified, and compiled the geologic map of Lathrop Wells on a topographic base, from which figure 1 of our report (*1*) was derived.

Wells *et al.* state that our composite unit Ql_5/Qs_5 (*1*), is oversimplified and does not "account for stratigraphic tephra" units separated by soil-bounded unconformities. The deposits in question were discussed in a paper by Turrin and Champion (*3*), which Wells *et al.* cite. These deposits of sand, silt, and lapilli-size tephra, supported in a matrix of eolian sand and silt, are immediately adjacent to the main cinder cone and overlie our unit Qs_5. We find no evidence (compositional, sedimentological, or granulometric) presented by Wells *et al.* (*4*) to support the volcanic origin of these lapilli-rich deposits. Turrin and Champion (*3*) have proposed that these deposits are cone-apron deposits derived from the nearby cone slope. Others (*5*) have also questioned the volcanic origin of these deposits.

Granulometry data on material from the basal portions of several of these deposits show that they contain 30 to 50% quartzofeldspathic eolian sand and silt (Fig. 1). This large proportion of eolian sand and silt, not mentioned by Wells *et al.* (*4*), cannot be accounted for by infiltration processes from overlying eolian units and indicates that these deposits are not volcanogenic in origin. Wells *et al.* and Crowe *et al.* (*6*) report without apparent documentation a thermoluminescence (TL) age of 9.9 ± 0.7 ka for these deposits and state that they can be traced continuously to the summit of the main cinder cone. This TL age is discordant with the ^{3}He exposure age [>51 ± 13 ka (*6, 7*)] for the cone rim. The paradox can be resolved if the "tephra" deposits (*4*) are not volcanic in origin, but are younger cone-apron deposits formed during subsequent erosion of the cinder cone. We conclude that the TL age of 9.9 ± 0.7 ka given (*6*) for these deposits is irrelevant to the age of volcanic activity at Lathrop Wells.

Wells *et al.* state that the ages we measured reverse the stratigraphic sequence of the volcanic events. Our analytical results—136 ± 8 ka for the older, composite units (Qs_5/Ql_5) and 141 ± 9 ka for the younger unit (Ql_3)—however, are statistically consistent with the stratigraphy within the stated analytical uncertainties. A difference of 5 ka between ages with σ uncertainties of 8 and 9 ka, respectively, is not statistically significant.

The ^{3}He cosmogenic exposure age dating method referred to by Wells *et al.* and Crowe *et al.* (*6*) is a developmental technique, and no analytical data for Lathrop Wells have been presented to our knowledge. Also, the ^{3}He-production rate as a function of latitude and time is in dispute (*8, 9, 10*). Exposure ages reflect time of exposure at the earth's surface and, as emphasized by Crowe *et al.* (*6*), always represent minimum ages for formation. Statistical comparison of the ^{3}He ages of the volcanic bombs from the cone rim yields a weighted mean of 31 ± 12 ka σ and a mean square of the weighted deviates (MSWD) (*11, 12*) of 39.7. This large MSWD indicates a high probability of a real difference in exposure ages for the volcanic bombs and supports our point about the danger of interpreting these ages as anything but minimum values. Because these ^{3}He age measurements are only minimums, they are consistent with our $^{40}Ar/^{39}Ar$ and K-Ar ages. Moreover, a U-Th disequilibrium age of 150 ± 40 ka for unit Ql_4 (our unit Ql_3) reported by Crowe *et al.* (*6*) supports our age determinations.

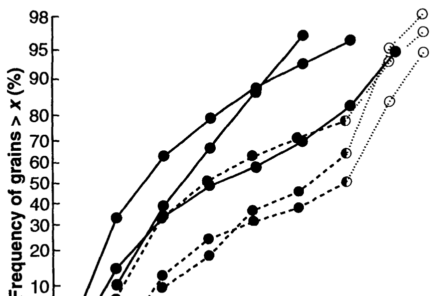

Fig. 1. Grain size distribution curve for scoria and cone-apron deposits from the Lathrop Wells volcanic center. Solid black lines and solid circles are grain size distribution curves of scoria and lapilli from the main cinder cone. Dashed and dotted lines show the grain-size distribution curves of the "tephra" deposits of Wells *et al.* (*4*). Dashed lines and solid circles indicate scoria and lapilli. Dotted lines and open circles indicate quartzofeldspathic eolian sand and silt.

In items 1, 2, and 3 Wells *et al.* criticize our use of weighted mean ages by arguing that the data are positively skewed, that we did not note the presence of "outliers" in our data set, and that we unsystematically discarded age determinations because of contamination.

We discussed these issues in our report (*1*) and elsewhere (*3, 13*). Samples affected by tuff xenoliths can be identified by their $^{37}Ar/^{39}Ar$ ratios (*14*), by their analytically distinct ages, or by both (*1*). Moreover, the rejection criteria of Ludwig (*11*) also identify the same four points as not being part of the same population. When the four contaminated samples are removed from the data set, it is normally distributed, as shown in our original figure 3 (*1*). Use of the weighted mean as the best estimate of the age is not only permissible but appropriate if the MSWD is less than or equal to one (*11, 12*).

In item 4, Wells *et al.* argue that our isochron plots (*1*) contain influential cases that could control the *y*-intercept. In the analysis of the isochron data, we did not identify any "influential" data points. The regression technique of York (*12*) does not permit unwarranted "influence" by individual points but, as with a weighted mean, accounts for the analytical precision of individual measurements. We eliminated unwarranted influence by contaminated samples with compositional and statistical parameters, as discussed above. Moreover, isochron and inverse-isochron ages and intercepts are presented for data subsets from each sample site presented by Turrin and Champion (*3*). In all cases the ages and intercepts are analytically indistinguishable at $P = 0.05$.

The discussion of ^{39}Ar recoil by Wells *et al.* is oversimplified (*15*). The K-Ar and $^{40}Ar/^{39}Ar$ ages from Lathrop Wells are concordant, and K-Ar ages are not subject to recoil. Unless phases that do not retain Ar or intergrown groundmass that cannot be resolved microscopically are present in whole-rock samples, ^{39}Ar recoil will not affect $^{40}Ar/^{39}Ar$ total-fusion ages (*16*). Petrographic and secondary ion-microprobe studies indicate that our Lathrop Wells samples are holocrystalline and that none have significant irresolvable intergrowths. In addition, our isochron plots have $^{40}Ar/^{36}Ar$ intercepts of 295 (*16*) and values for MSWD (*11*) of less than one, which indicates the absence of any substantial ^{39}Ar-recoil effects. Finally, recently obtained $^{40}Ar/^{39}Ar$ step-heating spectra (Fig. 2) show that there are no observable ^{39}Ar-recoil effects, which confirms the age of the Lathrop Wells volcanic center and precludes the possibility that our age estimate is the result of excess ^{40}Ar.

The assertion in item 6 by Wells *et al.* that the age determinations are from two different populations is predicated on an assumed difference which they do not specify. The material analyzed by the $^{40}Ar/^{39}Ar$ method are from splits of the same material on which the K-Ar analyses were performed. Statistical comparison shows that the K-Ar data and the $^{40}Ar/^{39}Ar$ data are analytically indistinguishable ($P = 0.05$) (*1*). These results are part of a Yucca Mountain Project symposium volume that is in preparation [reference 10 of (*1*)] (*13*). This paper was available to Wells *et al.* and Crowe *et al.* (*6*), and we would be pleased to provide it on request.

In their comments on our paleomagnetic work, Wells *et al.* are correct. As we have also stated (*17*), the angular difference between two paleomagnetic directions that results from geomagnetic secular variation can, by itself, only suggest a minimum age difference between volcanic units. When combined with other geologic information, however, it can be used to estimate absolute age differences. The small dispersion of paleomagnetic directions recorded in different basaltic centers near Yucca Mountain make it improbable that they sustain long eruption durations (*17*). Wood (*18*), in his review of 42 historically observed cinder cone eruptions, found that the median duration of the eruptions was 30 days and that 95% ended in 1 year or less.

We do rely on stratigraphy in our handling of the paleomagnetic data from the Lathrop Wells center. We described results for the two geologic units that we recognize. Paleomagnetic data are grouped by stratigraphic units into two distinct groups that are statistically distinguishable ($P = 0.0002$). The historic record, the minimum paleomagnetic directional variation, and the absence of a significant age difference between the volcanic units at the Lathrop Wells center all suggest a minimum eruption duration of about 100 years.

Preliminary paleomagnetic data from newly defined units Ql_6 and Ql_7 are described by Crowe *et al.* (*6*) as having natural remanent magnetization "directions that do not differ significantly from those reported by Turrin *et al.*" (*1*). This also suggests that the eruption at Lathrop Wells was brief. Champion (*17*) found only an 11% probability that the paleomagnetic directions obtained from units Ql_3 and Qs_5 were acquired at random times. If as many as seven independent geologic units exist, as stated by Crowe *et al.* (*6*), then the probability of random acquisition falls to $\leq 10^{-6}$ (*19*). A preliminary paleomagnetic data table was presented by Turrin *et al.* (*13*). An equal-area diagram showing final mean unit directions appeared in a study by Champion (*17*).

The statement by Wells *et al.* that "one-third of 16 reported samples from bombs on the main scoria cone" were rejected misrepresents our preliminary data set (*13*). Six samples taken from the cone slope showed a linear correlation between the slope-angle

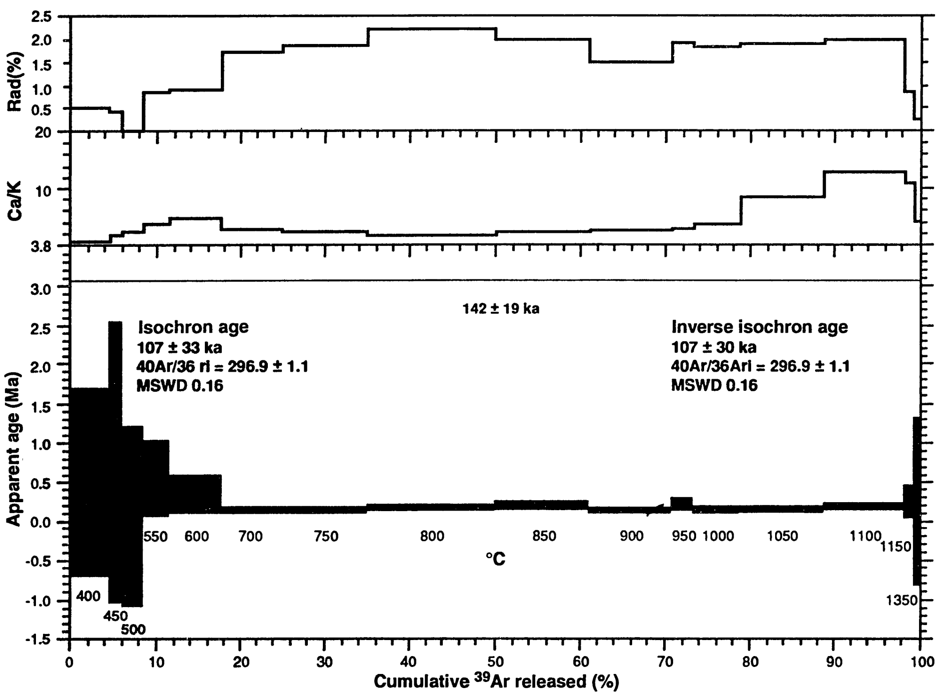

Fig. 2. $^{40}Ar/^{39}Ar$ release spectra from sample 3-86 of Turrin *et al.* (*3*). The *y* axis shows apparent age (Ma), Ca/K ratio, and percent radiogenic ^{40}Ar. The *x* axis shows cumulative percent ^{39}Ar released. The plateau age of the data is 142 ± 19 ka. Temperature (°C) is shown for each step; the step at 650°C was not measured because of a system malfunction.

at the collection site and the angular deviation of each sample from the mean paleomagnetic direction of the remaining samples. This relation suggests that these samples were rotated by a slope-dependent slumping process. Because of this observation, we collected 27 additional samples only from the crest of the cone rim, which gave us a total of 43 samples. The only other samples rejected from this set were eliminated with standard paleomagnetic criteria, namely, erratic directions of magnetization and high magnetic intensities related to lighting-induced isothermal remanent magnetization. An angular difference of only 0.3° was determined between the mean paleomagnetic direction of this "cone-rim" group and the unit Qs_5 samples. This result indicates a low probability that these units formed at random times (P = 0.0004) (*17*). These results and the absence of any geological unconformity or soil horizon within or between the cinder cone and adjacent scoria deposits of unit Qs_5 indicate that both deposits represent a single eruptive unit.

We find no contradiction between statements in our *Science* article (*1*) and those in our earlier paper (*13*). The 4.7° angular difference between units Ql_3 and Qs_5, which suggests a minimum eruption duration of 100 years for the Lathrop Wells center, is a more complex eruption model than previously thought (*20*). The indication that the Lathrop Wells center lasted more than 100 times longer than most historic cinder-cone eruptions (*18*) has few geologic precedents.

Wells *et al.* state that our conclusion (*1*) that the Lathrop Wells volcanic center is not polycyclic and is approximately 140 ka "could justify an assessment of decreased volcanic risk for Yucca Mountain." In contrast, Crowe (*21*) has said, "If the polycyclic model is correct, we would argue that the highest probability of event that might occur in the next 10,000 years or in the future, would be a recurrence in eruption at either Lathrop Wells or the Hidden Cone of the Sleeping Butte center[s]". Criticism of such confidence to predict future volcanic activity was recently voiced by a peer-review panel discussing U.S. Department of Energy plans for study of the Yucca Mountain repository (*22*).

Finally, geochemical data reported by Perry and Crowe (*23*) provide no quantifiable constraints on the duration of volcanic events, and we do not see their relevance to age dating. The slight variation in the chemical data (*23*) is consistent with monogenetic cinder-cone volcanism.

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19 December 1991; revised 27 May 1992; accepted 10 June 1992